Future prospects in the search for light hidden particles

Richard Jacobsson
We expect(ed?) TeV scale new physics with sizable couplings but…
…no tangible evidence for new physics and no hint of the scale!

What about solutions to (some/all) SM shortcomings below Fermi scale $E < G_F^{-1/2}$?

- **Known physics**
  - $\nu$, $e$, $\mu$, $q(udscb)$, $W$, $Z$, $t$
  - SUSY, extra dim.
  - Composite Higgs
  - Energy Frontier

- **Hidden Sector**
  - Intensity Frontier

- **Unknown physics**

- **Must have very weak couplings** ➔ “Light Hidden Sector”

- Received much less attention recently:
  - PS 191: early 1980s
  - CHARM: 1980s
  - NuTeV: 1990s
  - DONUT: late 1990s - early 2000

“The particle physicist and the cosmologist…”
New Physics prospects

- Two possibilities for Beyond Standard Model with light particles
  1. Wider theory exist at new high energy scale (SUSY, extra dim., etc) with degrees of freedom that stay relevant at low energies. Particles may be light by dynamic effects
  2. SM + Hidden Sector with light messengers is all there is up to Planck scale – no new visible scale
  3. or both…

  ➔ Natural assumption: *We know we have a dark sector*

- Powerful constraints imposed by cosmological and astrophysical observations
  - Relic dark matter density
  - Big Bang Nucleosynthesis
  - CMB
  - Structure formation
  - Supernovae and white dwarf cooling
  - Baryon asymmetry
  - …
New Physics prospects in Hidden Sector

\[ \mathcal{L}_{\text{World}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{mediation}} + \mathcal{L}_{\text{HS}} \]

- **Visible Sector**
  
  \[ G_{\text{SM}} = \text{SU}(3)_c \times \text{SU}(2)_L \times \text{U}(1)_Y \]
  
  (+SUSY)

  **Messenger interaction**
  
  "Portals"

- **Hidden Sector**
  
  SM singlets - Non-minimal with \( G_{\text{HS}} \)

  \[ \mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l = n+4} \frac{\mathcal{O}_{\text{HS}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n} \]

- New hidden particles are singlet under the SM gauge group

- Composite operators (hoping there is not just gravity...)
  
  Makes up "portals" between SM and Hidden Sector
  
  - No knowledge of hidden scale but hidden particles participating in portals may be light

  \[ \text{Dynamics of Hidden Sector may drive dynamics and anomalies of Visible Sector!} \]

  \[ \text{Dark Matter candidates comes for “free” – stable or unstable} \]
New Physics prospects in Hidden Sector

- **Standard Model portals:**

  - **D = 2: Vector portal**
    - Kinetic mixing with massive dark/secluded/paraphoton $A'$: $\frac{1}{2} \varepsilon F_{\mu \nu} F_{\mu \nu}^{HS}$
    - Motivated in part by idea of “mirror world” restoring L/R symmetry, dark matter (AMS $e^+$ excess), g-2 anomaly, ...

  - **D = 2: Scalar portal**
    - Mass mixing with dark singlet scalar $\chi$: $(g \chi + \lambda \chi^2)H^\dagger H$
    - Mass to Higgs boson and mass generation in dark sector, inflaton, dark phase transitions BAU, dark matter, ...

  - **D = 5/2: Neutrino portal**
    - Mixing with right-handed neutrino $N$ (Heavy Neutral Lepton): $Y_{1\ell} H^\dagger \bar{N}_{\ell} L_{\ell}$
    - Neutrino oscillation, baryon asymmetry, dark matter

  - **D = 4: Axion portal**
    - Mixing with Axion Like Particles, pseudo-scalars pNGB, axial vectors $a$: $\frac{a}{F} G_{\mu \nu} \bar{G}^{\mu \nu}, \frac{\partial a}{F} \bar{\psi} D_{\mu} \gamma_{5} \psi$, etc
    - Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale $F$
    - Extended Higgs, SUSY breaking, dark matter, possibility of inflaton, …
And higher dimensional operator portals

- Chern-Simons portal (vector portal)
- ...

SUper-SYmmetric “portals”

- Some of SUSY low-energy parameter space open to complementary searches
- Goldstino $S(P) : \frac{M_{\gamma \gamma}}{F}SF F_{\mu \nu}$
  - Massless at tree level but massive via loop corrections
  - Naturally light in no-scale SUGRA and GMSB
- Indirect production: heavy hadron decays $D \rightarrow \pi S(P)$ $D_s \rightarrow K^+ S(P)$
- Decay: $X \rightarrow \pi^+ \pi^-, \pi^0 \pi^0, l^+ l^-, \gamma \gamma$
- Neutralino in R-Parity Violating SUSY
  - LSP can decay into SM particles
  - Light neutralino with long lifetime $\tau_{\tilde{\chi}} < 0.1 s$ (BBN)
  - Production: heavy meson decays $D \rightarrow \nu \tilde{\chi}$, $D^\pm \rightarrow l^\pm \tilde{\chi}$
  - Decay: $\tilde{\chi} \rightarrow l^+ l^- \nu$
- Hidden Photinos, axinos and saxions...

A very large variety of models based on these or mixtures thereof

- Assumption here: invisible decay $\chi \chi \bar{\chi}$ is absent or sub-dominant, $m_\chi > \frac{1}{2} m_{portal}$, where $\chi$ hidden particle
Status of dark photon searches

- Mass $m_{A'} < \text{few GeVs}$, otherwise $\bar{p}$ excess in many models

- Production
  - Bremsstrahlung (e, p), direct QCD production $q\bar{q} \rightarrow A'$, $qg \rightarrow A'q$, meson decays ($\pi^0, \eta, \omega, \eta', \ldots$)
  - Electron fixed-target experiments
  - B, D factories
  - Proton beam-dumps!

Electrons fixed-target experiments

- B, D factories
- Proton beam-dumps!
**Status of dark photon searches**

- **B factories (D factories BESIII) (light resonance search)**
  - $e^+ e^- \rightarrow \Upsilon \rightarrow \gamma A'$, radiative decays $e^+ e^- \rightarrow \Upsilon(2) \rightarrow \Upsilon(1s) \pi^+ \pi^-$ where $\Upsilon(1s) \rightarrow \gamma A'$
  - BaBar (514 fb$^{-1}$): Generic search for neutral resonance with displaced vertex 1 – 50 cm,
    
    $$A' \rightarrow e^+ e^-, \mu^+ \mu^-, (e^\pm \mu^\mp), \pi^+ \pi^- K^+ K^-, (\pi^\pm K^\mp), 0.2 – 10 \text{ GeV}$$
  - Belle: Radiative decays $\Upsilon(2S) \rightarrow \Upsilon(1s) \pi^+ \pi^-$ → $\gamma$ + invisible (24.7 fb$^{-1}$ of $\Upsilon(2S)$ data);
    
    $$e^+ e^- \rightarrow A' \mu^+ \mu^-, A' \rightarrow l^+ l^-, \pi^+ \pi^-, K^+ K^-$$, Prompt and displaced vertices up to 10cm

- **Electron dumps: HPS** $A' \rightarrow e^+ e^-, \mu^+ \mu^-, 0.02 – 1 \text{ GeV/c}^2$ (*PADME, NA64*)

- **NA48/62:** $\pi^0 \rightarrow \gamma A'$, 9-70 MeV/c$^2$
  - Prospects $K^+ \rightarrow \pi^+ A'$, $A' \rightarrow l^+ l^-$ lower background and higher acceptance, 10 – 350 MeV/c$^2$

- **LHC:** Not ideal….
  - Large background and not many photons
  - Displaced vertices: “displaced lepton-jets”
Similar signatures to dark photon

- Interpretation of [limits on] signal in framework of model

Production:

- Rare meson decays e.g. $B \rightarrow K^{(*)}\chi$, $K \rightarrow \pi\chi$, $\Upsilon \rightarrow \gamma + visible/invisible$
  - Production in D decays suppressed, i.e. $(m_{\chi}^2 |V_{ts} V_{tb}|)^2 / (m_{\chi}^2 |V_{cb} V_{ub}|)^2$
  - (Dark Higgsstrahlung)
  - Direct $p + target \rightarrow X\chi$
## Status of dark scalar searches

- **BaBar**: $\Upsilon \to \gamma \chi$, $\chi \to \mu\mu, \tau\tau, hh$
  
- **Belle**: $B \to K\chi$, $\chi \to \mu^+\mu^-$, $\Upsilon \to \gamma + invisible$
  
- **LHCb (3fb⁻¹)**:
  - $B \to K\chi$, $\chi \to \mu^+\mu^-$, both prompt and displaced vertices
  - Analysis largely background free $\rightarrow$ sensitivity scales with yield of B
Production:
- Leptonic, semi-leptonic decays of hadrons
- $W, Z$ decays
- $\Gamma_N \sim |V_{\alpha N}|^2 G_F^2 M_N^5$

Below BAU (e.g. $N_2, N_3$ in $\nu$MSM)

**B factories/LHCb**

**Hadron colliders**

**Z factories**
Below BAU (e.g. $N_2, N_3$ in $\nu$MSM)
Status of ‘heavy’ neutrino searches

- BABAR ($4.7 \times 10^8 B\bar{B}$, 561 fb⁻¹): $B^+ \rightarrow X^- l^+ l'^+; \ X^- = K^-, \pi^-, \rho^-, K^{*-}, D^-; \ l^+ l'^+ = e^+, \mu^+$
- Belle ($7.7 \times 10^8 B\bar{B}$, 711 fb⁻¹): $B \rightarrow X l N, \ X = D^{(*)}, \ \text{light meson or nothing}; \ N = l\pi, \ l = e, \mu$
- LHCb (3 fb⁻¹): $B^- \rightarrow X^+ \mu^- \mu^+; \ X^+ = \pi^+, D^+, D^{*+}, D^0_s^+, D^{0\pi^+}, K^+$
  \[ D^+_s \rightarrow \pi^- \mu^+ \mu^+ \]
- LHC (ATLAS/CMS ~20 fb⁻¹): $W \rightarrow N l^\pm; \ N \rightarrow l^\mp W^\pm; \ W \rightarrow l\nu, q\bar{q}, \ ~10^9 \nu$’s for each 25 fb⁻¹ from W’s
- NA48/NA62: $K^+ \rightarrow l^+ N, \ N \rightarrow l\pi, l\rho; \ 0.1 – 0.4 \text{ GeV}
  \[ D^+_s \rightarrow l^+ N, \ N \rightarrow l\pi, l\rho; \ 0.4 – 1.5 \text{ GeV, to be evaluated} \]
SHiP Physics case

- Large and highly interesting territory still remains!
- SHiP has significant sensitivity to all of these up to $O(10) \text{ GeV}$!

- SHiP Physics Proposal
  - >80 theorist authors
  - >200 pages
  - >1000 references!

- Setting limits is “easy” but theorist home work:
  - In case of discover, how do we call the new particle(s)!!?
Cosmologically interesting and experimentally accessible $m_{HS} \sim \mathcal{O}(MeV \rightarrow GeV)$

- Production in $\pi$, K, D, B decays, photons
- Most common 2-body decays

<table>
<thead>
<tr>
<th>Models</th>
<th>Final states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrino portal, SUSY neutralino</td>
<td>$\ell^+ \pi^-, \ell^+ K^+, \ell^+ \rho^+, \rho^+ \rightarrow \pi^+ \pi^0$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$\ell^+ \ell^-$</td>
</tr>
<tr>
<td>Vector, scalar, axion portals, SUSY sgoldstino</td>
<td>$\pi^+ \pi^-, K^+ K^-$</td>
</tr>
<tr>
<td>Neutrino portal, SUSY neutralino, axino</td>
<td>$\ell^+ \ell^- \nu$</td>
</tr>
<tr>
<td>Axion portal, SUSY sgoldstino</td>
<td>$\gamma \gamma \pi^0 \pi^0$</td>
</tr>
<tr>
<td>SUSY sgoldstino</td>
<td></td>
</tr>
</tbody>
</table>

Production and decay rates are very suppressed relative to SM

- Production branching ratios $\mathcal{O}(10^{-10})$
- Large neutrino background
- Travel unperturbed through ordinary matter
- Long-lived objects

- Challenge is background suppression requires extremely careful estimation

Fixed-target ("beam-dump") experiment with large decay volume

- Side benefit: Optimizing for heavy meson decays also optimizes facility for $\nu_\tau$ physics
  - $Br(D_s \rightarrow \tau + \nu_\tau) \sim 5.6% : 10^{15}$
Proposal: ‘Beam dump’-like experiment at the SPS

- SPS: $4 \times 10^{13}$ / 7s @ 400 GeV $\rightarrow$ 500 kW $\rightarrow$ $2 \times 10^{20}$ in 5 years (similar to CNGS)

1. Parallel operation with CERN North Area LHC, AWAKE, etc

2. Slow beam extraction of 1s
   - Beam dilution on target
   - Reduce combinatorial background

3. As uniform extraction as possible for target and combinatorial background/occupancy
   1. Muon shield to range out flux of muons
   2. Away from walls and minimize surrounding structures to reduce neutrino/muon interactions in proximity of detector

7. Evacuated detector volume to reduce neutrino interactions

8. Detector as close as possible to target to maximize acceptance
   - Hidden particles in D and B decays have significant $p_T$
Initial reduction of beam induced background:
- Heavy target
- Hadron absorber
- Muon shield

→ Without: Rate at detector $5 \times 10^9$ muons / $5 \times 10^{13}$ p.o.t.
→ Biased towards higher momenta muons due to heavy target
Residual background sources

- **Residual backgrounds sources:**
  1. **Neutrino inelastic scattering** (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu \pi \nu$)
  2. **Muon inelastic scattering**
  3. **Muon combinatorial** (e.g. $\mu\mu$ with $\mu$ mis-ID)
  4. **Neutrons**
  5. **Cosmics**

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**Diagram:**
- Neutrino
- Muon
- Muon shield
- E.m. and hadrons
- Vacuum
- Neutrons
- Various particles (e.g. $K_L, K_S, \Lambda, n, \gamma$)
- Occupancy + combinatorial

**Table:**

<table>
<thead>
<tr>
<th>Particle</th>
<th>Fraction Entering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>1.98</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>$3.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$K_S^0$</td>
<td>$3.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$K_L^0$</td>
<td>0.5%</td>
</tr>
</tbody>
</table>

*Not to scale!*
Overview of SHiP (TP)

Several technological challenges
SHiP Location

- Proposed location by CERN beams and support departments
  - $4 \times 10^{13}$ protons on target at 400 GeV / 7s with slow extraction
  - $10^6$ spills / year $\Rightarrow 4 \times 10^{19}$ p.o.t.

SPS is a unique machine!
Civil engineering close to existing infrastructures

- 8m safety margin required during operation of NA
- 20 months required for work package to make junction cavern and rebuild beamline
- 4-5 years in total
Design considerations with $4 \times 10^{13}$ p / 7s

- 355 kW average, 2.56 MW during 1s spill
  - High temperature
  - Compressive stresses
  - Atomic displacement
  - Erosion/corrosion
  - Material properties as a function of irradiation
  - Remote handling (Initial dose rate of 50 Sv/h…)

- Hybrid solution: Mo allow TZM ($4\lambda$) + W($6\lambda$)

### Table:

<table>
<thead>
<tr>
<th></th>
<th>DONUT 1)</th>
<th>CHARM 2)</th>
<th>SHiP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target material</td>
<td>W-alloy</td>
<td>Cu (variable $\rho$)</td>
<td>TZM + pure W</td>
</tr>
<tr>
<td>Momentum (GeV/c)</td>
<td>800</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>Intensity</td>
<td>$0.8 \times 10^{13}$</td>
<td>$1.3 \times 10^{13}$</td>
<td>$4 \times 10^{13}$</td>
</tr>
<tr>
<td>Pulse length (s)</td>
<td>20</td>
<td>$23 \times 10^{-6}$</td>
<td>1</td>
</tr>
<tr>
<td>Rep. rate (s)</td>
<td>60</td>
<td>$\sim 10$</td>
<td>7.2</td>
</tr>
<tr>
<td>Beam energy (kJ)</td>
<td>1020</td>
<td>830</td>
<td>2560</td>
</tr>
<tr>
<td>Avg. beam power (spill) (kW)</td>
<td>51</td>
<td>$3.4 \times 10^{7}$ (fast)</td>
<td>2560</td>
</tr>
<tr>
<td>Avg. beam power (SC) (kW)</td>
<td>17</td>
<td>69</td>
<td>355</td>
</tr>
<tr>
<td>POT</td>
<td>Few $10^{17}$</td>
<td>Few $10^{18}$</td>
<td>$2 \times 10^{20}$</td>
</tr>
</tbody>
</table>
Active muon shield

- Muon flux limit driven by emulsion based $\nu$-detector and “hidden particle” background
- Passive and magnet sweeper/passive absorber options studied:
  - Conclusion: Shield based entirely on magnetic sweeping with $\int B_y \, dl \sim 86$ Tm
- $<7 \times 10^3$ muons / spill ($E_\mu > 3$ GeV) which can potentially produce V0 ($K_L$)
- Negligible occupancy

$\Rightarrow$ Challenges: flux leakage, constant field profile, modelling magnet shape

Prompt dose rates in the experimental hall 4E13 p.o.t. / 7s

2800 tonnes

48m
HS detector as in TP

Detector concept

1. Large decay volume
2. Full reconstruction and particle identification of final states with $e, \mu, \pi^{\pm}, \gamma (\pi^0, \rho^{\pm})$, ($\nu$), and decays in flight
   - Magnetic spectrometer, electromagnetic calorimeter, hadron calorimeter/muon detector
   - Extended particle ID under investigation
3. Background identification
   - Timing detectors, surrounding and front veto taggers
Residual backgrounds sources:

1. **Neutrino inelastic scattering** (e.g. $\nu_\mu + p \rightarrow X + K_L \rightarrow \mu \pi \nu$) → Detector under vacuum, accompanying charged particles (tagging, timing), topological

2. **Muon inelastic scattering** → Accompanying charged particles (tagging, timing), topological

3. **Muon combinatorial** (e.g. $\mu \mu$ with $\mu$ mis-ID) → Tagging, timing and topological

4. **Neutrons** → Tagging, topological

5. **Cosmics** → Tagging, timing and topological

Under study:

1. Double wall vessel with liquid scintillator: Cylinder Background Tagger
2. Front window with liquid scintillator/plastic scintillator: Front Background Tagger
3. Downstream high-resolution timing detector
4. (Upstream VETO chamber)
   → **Note:** Concept of VETO → deadtime = rate * time resolution/1s

5. Muon system of neutrino detector
Estimated need for vacuum: $10^{-3}$ mbar

- Based on $\nu$-flux: $2 \times 10^4 \nu$-interactions/$2 \times 10^{20}$ p.o.t. at $p_{\text{atm}}$

**Vacuum vessel**

- $10 \text{ m} \times 5 \text{ m} \times 60 \text{ m}$;
- Walls thickness: 8 mm (Al) / 30 mm (SS);
- Walls separation: 300 mm;
- Liquid scintillator volume: $\sim 360 \text{ m}^3$;
- 1500 WOMs (8 cm $\times$ 8 cm WOM + PMTs);
- Metal weight (SS, no support): $\sim 480 \text{ t}$.

**Low power magnet designed**

- Field integral: $0.65 \text{Tm}$ over 5m
- Current: 2500 A (1.7 A/mm²)
- Power consumption < 1 MW
- Weight: $\sim 800 \text{ tonnes}$

<table>
<thead>
<tr>
<th>LAB (Linear alkyl benzene)</th>
<th>-</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 diphenyl oxazole (PPO)(C15H11NO)</td>
<td>3g/l</td>
</tr>
</tbody>
</table>
Follows the OPERA concept
Unique capability of detecting all three neutrino flavours

- Neutrino interaction +
  - $\nu_e$: electrons producing e.m. shower in emulsion target
  - $\nu_\mu$: muons identified by target tracker and the muon spectrometer of the $\nu_\tau$ detector
  - $\nu_\tau / \bar{\nu}_\tau$: $\tau$ decay vertices in emulsion target

Separation between $\nu_\tau$ and $\bar{\nu}_\tau$ by charge measurement

- charge of hadrons is measured by CES
- charge of muons is measured by CES and magnetic spectrometer

### Table 1: Efficiency of Charge Measurement

<table>
<thead>
<tr>
<th></th>
<th>$\tau \rightarrow \mu X$</th>
<th>$\tau \rightarrow h X$</th>
<th>$\tau \rightarrow 3h X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct charge</td>
<td>70%</td>
<td>49%</td>
<td>94%</td>
</tr>
<tr>
<td>Wrong charge</td>
<td>0.5%</td>
<td>1.0%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>
Physics performance

$2 \times 10^{20}$ pot’s in ~5 years of SPS operation
Background summary: no evidence for any irreducible background

- No events selected in MC ➔ Expected background UL @ 90% CL
Prospects for dark photons

SHiP will have unique sensitivity
Prospects for hidden scalars

\[
\sin^2 \theta \quad \text{vs} \quad m_S \text{ (GeV/c}^2) \]

- SHiP
- B (visible)
- B (invisible)
- CHARM
- LHCb

\[ e^+ e^-, \mu^+ \mu^-, \pi^+ \pi^- \]

\[ 3 \text{ fb}^{-1} \]

KEK seminar, Japan, April 19, 2016

R. Jacobsson (CERN)
Prospects for HNL

Visible decays = At least two tracks crossing the spectrometer
- Ex. For $m_N = 1$ GeV with $U^2 = 10^{-8}$ and $BR(N \rightarrow \mu \pi) = 20\%$, expect ~330 signal events

$U_e^2: U_\mu^2: U_\tau^2 \sim 52:1:1$, inverted hierarchy
$U_e^2: U_\mu^2: U_\tau^2 \sim 1:16:3.8$, normal hierarchy
$U_e^2: U_\mu^2: U_\tau^2 \sim 1:11:11$, normal hierarchy

Scenarios for which baryogenesis was numerically proven
Prospects for HNLs

- BELLE-2 using $B \rightarrow XlN$, where $N \rightarrow l\pi$, $l = e, \mu$, and $X$ reconstructed using missing mass may go well below $10^{-4}$ in $0.5 < M_N < 5$ GeV

- LHCb, ATLAS/CMS

- HNLs at FCC 2 – 90 GeV
  - FCC-ee/CEPC, H-factory
  - FCC-hh: 100 TeV pp

- ILC >100 GeV

Displaced vertexes between 100 $\mu$m and 5 m and $10^{13} Z^0$
$\nu_\tau$-physics in brief
Most elusive particle in SM
- DONUT experiment 9 events with 1.5 expected background
- OPERA experiment 5 events from $\nu_\mu \rightarrow \nu_\tau$ oscillation
  ➔ No distinction between $\nu_\tau$ and $\bar{\nu}_\tau$

→ Expected interactions in SHiP with 6-tonne target

→ Reconstructed events and charm background events

→ Neutrino induced charm events
SM Physics: Prospects for $\nu_\tau (\nu_e, \nu_\mu)$

1. First observation of $\nu_\tau$ interaction
2. Measurement of $\nu_\tau$ and $\bar{\nu}_\tau$ cross-sections

$$\frac{d^2\sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M E_\nu}{\pi(1 + Q^2/M_W^2)^2} \left( y^2 x + \frac{m_\tau^2 y}{2 E_\nu M} \right) F_1 + \left[ (1 - \frac{m_\tau^2}{4E_\nu^2}) - (1 + \frac{M x}{2E_\nu}) \right] F_2$$

$$\pm \left[ xy(1 - \frac{y}{2}) - \frac{m_\tau^2 y}{4E_\nu M} \right] F_3 + \frac{m_\tau^2 (m_\tau^2 + Q^2)}{4E_\nu^2 M^2 x} F_4 - \frac{m_\tau^2}{E_\nu M} F_5,$$

- Allow extraction of F4 and F5 structure functions from charged current neutrino-nucleon DIS
- Beyond SM

3. $\nu_e$ cross section at high energy
4. Testing strange quark content of nucleon through charm production

5. Normalization of hidden particle search
6. LNU
SHiP Technical Proposal

- Technical Proposal
  - 243 members from 45 institutes in 14 countries
  - 250 pages
  - 200 pages of complementary documents outlining beam, target, RP, and civil engineering by CERN task force

- TP Addendum to SPSC Oct. 2015
  - Updates on backgrounds, sensitivity, comparison with other facilities, and schedule and resources
Organization and schedule
### 10 years from TP to data taking

- Schedule optimized for minimal interference with operation of North Area
  - Preparation of facility in four clear and separate work packages (junction cavern, beam line, target complex, and detector hall)
  - Use of Long Shutdown 3 for junction cavern and first short section of SHiP beam line

- Comprehensive Design Study 2016 – 2018: Starting now! ➔ Update of European HEP strategy 2018
- Construction / production 2021 –
- Data taking 2026 (start of LHC Run 4)
SHiP Collaboration at the time of TP:
- 250 members from 45 institutes in 14 countries
- Admission of several institutes pending

Current commitments for preparation of TP and CDR

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<tr>
<th>Component</th>
<th>Countries</th>
<th>Institutes</th>
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<td>Beamline and target</td>
<td>CERN</td>
<td>CERN</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>CERN</td>
<td>CERN</td>
</tr>
<tr>
<td>Muon shield</td>
<td>UK</td>
<td>RAL, Imperial College, Warwick</td>
</tr>
<tr>
<td>HS vacuum vessel</td>
<td>Russia</td>
<td>NRC KI</td>
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<tr>
<td>Straw tracker</td>
<td>Russia, CERN</td>
<td>JINR, MEPhI, PNPI, CERN</td>
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<td>HS spectrometer magnet</td>
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<td></td>
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<td>ITEP, Orsay, IHEP, INFN-Bologna</td>
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<td>Muon</td>
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<tr>
<td>Surrounding background tagger</td>
<td>Germany, Russia</td>
<td>INFN-Ferrara, INR RAS, MEPHi</td>
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<tr>
<td>Timing detector and upstream veto</td>
<td>France, Italy, Russia, Switzerland</td>
<td>Zurich, Geneva, INFN-Cagliari, Orsay, LPNHE</td>
</tr>
<tr>
<td>Tau neutrino emulsion target</td>
<td>Italy, Japan, Russia, Turkey</td>
<td>INFN-Naples, INFN-Bari, INFN-Lab. Naz. Gran Sasso, Nagoya, Nihon, Aichi, Kolkata, Moscow SU, Lebedev, Toho, Middle East Technical University, Ankara</td>
</tr>
<tr>
<td>Tau neutrino tracker (GEM)</td>
<td>Italy, Russia</td>
<td>INFN-Lab. Naz. Frascati, INFN-Naples, INFN-Roma, MEPHi</td>
</tr>
<tr>
<td>Tau neutrino detector magnet</td>
<td>Italy</td>
<td>INFN-Lab. Naz. Frascati, INFN-Bari, INFN-Naples, INFN-Roma, MEPhl</td>
</tr>
<tr>
<td>Tau neutrino tracking (RPC)</td>
<td>Italy</td>
<td>INFN-Lab. Naz. Gran Sasso, INFN-Naples, INFN-Roma</td>
</tr>
<tr>
<td>Tau neutrino tracker (drift tubes)</td>
<td>Germany</td>
<td>Hamburg</td>
</tr>
<tr>
<td>Online computing</td>
<td>Denmark, Russia, Sweden, UK, CERN</td>
<td>Niels Bohr, Uppsala, UCL, YSDA, LPHNE, CERN</td>
</tr>
<tr>
<td>Offline computing</td>
<td>Russia, CERN</td>
<td>YSDA, CERN</td>
</tr>
<tr>
<td>MC simulation</td>
<td>Bulgaria, Chile, Germany, Italy, Russia, Switzerland, Turkey, UK, Ukraine, USA, CERN</td>
<td>INFN-Napoli, Zurich, Geneva and EPFL Lausanne, Valparaíso, Berlin, PNPI, NRC KI, SINP MSU, MEPhl, Middle East Technical University, Ankara, Bristol, YSDA, Imperial College, Florida, Kyiv, CERN</td>
</tr>
</tbody>
</table>
Bright future for Dark Sector

- Very much increased interested for Hidden Sector after LHC Run 1

SHiP is a GP experiment for HS exploration in largely unexplored domain

- Also unique opportunity for $\nu_\tau$ physics, direct Dark Matter search, ...

Facility and physics case based on the current injector complex and SPS

- $2\times10^{20}$ at 400 GeV in 5 nominal years by “inheriting” CNGS share of the SPS beam time from 2026
- Yield SHiP@CERN / FNAL (Bkg=0) : HNLs: 1.5x / Dark photons: ~1x / Dark scalar: 400x / $\nu_\tau$: 7x
- JPARC charm production 1/200 (Dark photons: ~1x)

SHiP complements the current NP searches at energy and intensity frontier

Technical Proposal and Physics Proposal submitted in April 2015

Next phase: Requested to produce Comprehensive Design 2016 – 2018

Input to update of European HEP strategy 2018 - 2019
Spare slides
SPS Committee review

Technical Proposal and Physics Proposal submitted April 2015

⇒ 9 months review with SPSC

Official conclusion from SPSC

The SPSC has reviewed the proposal for “A Facility to Search for Hidden Particles (SHiP) at the CERN SPS” (Technical Proposal P-350 and Physics case P-350-ADD-1), submitted in April 2015 following an earlier submission of the Expression of Interest EoI-010 in October 2013. The review included several lists of questions sent to the proponents, which were all answered including submission of a proposal addendum P-350-ADD-2 in October 2015.

In the review process the Committee was impressed by the dedication of the SHiP proponents and their responsiveness to the Committee’s requests. In particular significant progress has been made since the EoI, along the lines of the SPSC112 recommendations, including optimisation of the proton beam dump design, broadening of the physics case and adaptation of the SHiP scheduling to external constraints. The CERN SPS offers a unique opportunity for the proposed programme and the SHiP proponents have the potential strength to build the proposed detector setup.

The main physics motivation of SHiP is to explore the domain of hidden particles, searching in particular for new scalar, fermionic and vector particles. These would be produced in a proton beam dump at 400 GeV, either directly or from decays of charm or beauty particles. The experiment would be sensitive to a hitherto unexplored region of parameter space, spanning masses from a few hundred MeV to a few GeV and over two orders of magnitude in squared couplings. The main experimental signature involves two charged decay tracks, and will be complemented by decays to neutral particles. The experiment is also proposed to be equipped with an emulsion target, which would allow for unprecedented tau neutrino and antineutrino measurements and valuable QCD studies. Furthermore it would extend the hidden sector search to scattering of dark matter particles. The facility could accommodate additional detectors extending the range of dark matter searches. The SPSC supports the motivation for the search for hidden particles, which will explore a domain of interest for many open questions in particle physics and cosmology, and acknowledges the interest of the measurements foreseen in the neutrino sector. SHiP could therefore constitute a key part of the CERN Fixed Target programme in the HL-LHC era.

The SPSC supports the updated SHiP schedule, which takes into account the HL-LHC preparation constraints during LS2, and defers any significant civil engineering investments for SHiP to the period following full approval of SHiP. The SPSC notes that, in this updated schedule, the time scale for the SHiP comprehensive design study, required for a final decision, coincides with the expected revision of the EU HEP strategy. The Committee also notes the plans of the incoming CERN Management to set up a working group to prepare the future of the CERN Fixed Target programme after LS2, as input to the next EU strategy update. In this context the SPSC recommends that the SHiP proponents proceed with the preparation of a Comprehensive Design Report (CDR), and that this preparation be made in close contact with the planned Fixed Target working group.

Preparation of the CDR should include further optimisation of the beam dump facility in the direction of a multipurpose area, test beams of detector prototypes where needed, detailed simulations of the detector response to all signal and background signatures, further theoretical studies of expected signals and comparisons with alternative search programmes. The Committee encourages the proponents to define a programme of measurements concerning production of charm in a SHiP-like target, important for normalisation purposes. The SPSC also encourages the proponents to further explore the potential benefit of inputs from the ongoing NA62 experiment to strengthen the experimental evaluation of SHiP backgrounds and systematics. The resources needed for the preparation of the SHiP CDR in the coming years should be secured within a MoU between CERN and the SHiP proponents’ institutes.
New phase (face) of SHiP

- Begin with re-optimization by revisiting
  - Muon shield including superconducting option, magnetization of hadron stopper
  - Evacuation of decay volume including the option of helium balloon
  - Shape of decay volume, conical to get closer
  - Implications for the spectrometer tracker (resolution) – detector technologies
  - Extended PID for neutral modes, three body decays etc – detector technology
  - Requirement on background taggers (granularity, pointing)
  - Implication for tau neutrino detector
  - ...

- Prototyping in 2017 and conclusions with updated sensitivities and cost in 2018
We expect(ed?) TeV scale new physics with sizable couplings but…

…no tangible evidence for new physics and no hint of the scale!

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \delta C \left[ \frac{\epsilon^{NP}}{\Lambda_{NP}^2} \right] \]
Phenomenology of some groups of physics models for SHiP
Massive dark (hidden, secluded, para-) photon

- Motivated in part by idea of “mirror world” restoring symmetry between left and right and constituting dark matter, positron excess, g-2 anomaly, ...
- SM portal through kinetic mixing with massive dark/secluded/paraphoton $V$

\[ \mathcal{L} = \frac{1}{2} \varepsilon F_{\mu \nu}^{SM} V_{H S}^{\mu \nu}, \text{ also mixing with } Z \]

Predominant dark photon production at SPS

- Proton bremsstrahlung from quasi-elastic $pp \rightarrow ppV$
- Meson decays ($\pi^0, \eta, \omega, \eta', ...$)
- Direct QCD production $q\bar{q} \rightarrow V, qg \rightarrow Vq$
- Lifetime limit from BBN: $\tau_\gamma < 0.1s$

Dark photon decays

- Visible $e^+e^-, \mu^+\mu^-, q\bar{q} (\pi^+\pi^-, ...)$, ...
- Invisible $\chi \bar{\chi}$, $m_\chi < \frac{1}{2} m_V$, where $\chi$ hidden sector particle

Decay branching ratios

- Visible $e^+e^-$, $\mu^+\mu^-$, $q\bar{q}$ ($\pi^+\pi^-$, ...), ...
- Invisible $\chi \bar{\chi}$, $m_\chi < \frac{1}{2} m_V$, where $\chi$ hidden sector particle

KEK seminar, Japan, April 19, 2016

D = GeV^2: Vector portal

Phys. Rev. D 90, 035022
Singlet dark scalar $S$

- Motivated by possibility of inflaton in accordance with Planck and BICEP measurements, giving mass to Higgs boson and right-handed neutrinos, dark phase transitions BAU, Dark Matter, dark Naturalness…, etc
- SM portal through mass mixing with the SM Higgs: $\lambda$

$$\mathcal{L} = (gS + \lambda S^2)H^\dagger H$$

Production
- Direct $p + \text{target} \rightarrow X + S$
- Meson decays e.g. $B \rightarrow KS$, $K \rightarrow \pi S$
  - Production in D decays suppressed, i.e. $(m_s^2 |V_{ts}^* V_{tb}|^2)/(m_b^2 |V_{cb}^* V_{ub}|^2)$
- Lifetime $\tau \propto \sin^{-2} \rho$

Decay modes:
Extension of SM with one massive right handed Majorana/Dirac neutrino per family

- Motivated by neutrino oscillation, baryon asymmetry and Dark Matter

\[ Y_{f\ell} H^T \bar{N}_1 L_\ell \] lepton flavour violating term results in mixing between \( N_1 \) and SM active neutrinos

\[ \Rightarrow \] Oscillations in the mass-basis and CP violation

\[ \Rightarrow \] Type I See-Saw with Majorana \( m_R >> m_D (= Y_{f\ell} v) \)

Four “popular” \( N \) mass ranges:

<table>
<thead>
<tr>
<th>( N ) mass</th>
<th>( v ) masses</th>
<th>eV ( v ) anomalies</th>
<th>BAU</th>
<th>DM</th>
<th>( M_H ) stability</th>
<th>direct search</th>
<th>experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>GUT see-saw</td>
<td>10^{10} \text{GeV}</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>NO</td>
</tr>
<tr>
<td>EWSB</td>
<td>10^2 \text{GeV}</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES \text{LHC}</td>
</tr>
<tr>
<td>v MSM</td>
<td>keV - GeV</td>
<td>YES</td>
<td>NO</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>\text{a la CHARM}</td>
</tr>
<tr>
<td>eV scale</td>
<td>eV</td>
<td>YES</td>
<td>YES</td>
<td>NO</td>
<td>NO</td>
<td>YES</td>
<td>\text{a la LSND}</td>
</tr>
</tbody>
</table>
Role of $N_1$ with a mass of $\mathcal{O}$(keV) ➔ Dark Matter

Role of $N_2$ and $N_3$ with a mass of $\mathcal{O}(m_q/m_{l\pm})$ (100 MeV – GeV): ➔ Neutrino oscillations and mass, and BAU

Assumption that $N_I$ are $\mathcal{O}(m_q/m_{l})$: No new energy scale!

- $Y_{l\ell} = \mathcal{O}\left(\sqrt{\frac{m_{\text{atm}} m_{l}}{v}}\right) \sim 10^{-8}$ ($m^R = 1 \text{ GeV}, m_\nu = 0.05 \text{ eV}$)
- $U^2 \sim 10^{-11}$

$N_1$ Subdominant radiative decay

$E_\gamma = \frac{M_{N_1} c^2}{2}$
HNL production and decay

- Predominant production in mixing with active neutrino from leptonic/semi-leptonic weak decays of heavy mesons
  - $D_s \rightarrow l N$, ($\tau \rightarrow X \nu_\tau$) $U_{e,\mu,\tau}^2$ and $N_{N} \leq M(D_s) - m_l$, ($N_{N} \leq M(\tau) - M(X)$)
  - $D \rightarrow l K N$ $U_{e,\mu}^2$ and $N_{N} \leq M(D_s) - m_l$
  - $B_{(s)} \rightarrow D_{(s)} l N$ $U_{e,\mu,\tau}^2$ and $N_{N} \leq M(B_{(s)}) - M(D_{(s)}) - m_l$
  - $B \rightarrow l N$ ($B \rightarrow l \pi N$) $U_{e,\mu,\tau}^2$ and $N_{N} \leq M(B) - m_l$, $Br \propto V_{ub}^2/V_{cb}^2$

$\Rightarrow$ Branching ratios $\mathcal{O}(10^{-7} - 10^{-8})$

- Very weak HNL-active neutrino mixing $\rightarrow N_{2,3}$ much longer lived than SM particles
  $\Rightarrow$ Typical lifetimes $> 10 \mu s$ for $M_{N_{2,3}} \sim 1 GeV$ $\rightarrow$ Decay distance $\mathcal{O}(km)$

- Decay modes
  - $N \rightarrow h^0 \nu$, with $h^0 = \pi^0, \rho^0, \eta, \eta'$
  - $N \rightarrow h^\pm l^\mp$, with $h^\pm = \pi^\pm, \rho^\pm$
  - $N \rightarrow 3\nu$
  - $N \rightarrow l^\pm l'^\mp \nu$

$\Rightarrow$ Total rate depend on $\mathcal{U}^2 = \sum_{l=2,3} \left| U_{\ell l} \right|^2$

- Relation between $U_{e}^2, U_{\mu}^2$ and $U_{\tau}^2$ depends on flavour mixing

- Decay mode Branching ratio
  - $N_{2,3} \rightarrow \mu/e + \pi$ 0.1 - 50 %
  - $N_{2,3} \rightarrow \mu^-/e^- + \rho^+$ 0.5 - 20 %
  - $N_{2,3} \rightarrow \nu + \mu + e$ 1 - 10 %
Axion Like Particles, pseudo-scalars pNGB, axial vectors $a$

- Appear in extended Higgs, SUSY breaking, motivated by coupling with dark sector, possibility of inflaton, etc
- Generically light pseudo-scalars arise in spontaneous breaking of approximate symmetries at a high mass scale $F$
  - Couplings suppressed by the breaking scale $F$ and masses are light $\sim \Lambda/F^2$
- SM portal through mixing with gauge bosons and fermions

$$\mathcal{L} = \frac{a}{F} G_{\mu\nu} \tilde{G}^{\mu\nu} + \frac{\mu a}{F} \bar{\psi} i\gamma_\mu \gamma_5 \psi + \text{etc}$$

Production
- Resonant production from Drell-Yan photons
- Production from mixing with pions and heavy meson decays

Decays
- Decays to $e^+e^-, \mu^+\mu^-$, hadrons above 1 GeV
- Decays to photon pair
ALP searches

- Production:
  - Primakoff production, mixing with pions and heavy meson decays
  - $\alpha \rightarrow \gamma\gamma, \mu^+\mu^-$

![Diagrams showing Primakoff production and meson decays](image)

![Graph showing ALP searches with SN1987a, CHARM, and (g-2)$_\mu$ regions](image)

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KEK seminar, Japan, April 19, 2016

R. Jacobsson (CERN)
SUSY with light long-lived partners

- The absence of SUSY below TeV and the relatively large Higgs mass leads to increasing electro-weak fine-tuning of the SUSY parameters
  - How to make SUSY natural?
    - Lowering breaking scale $\Lambda_{SUSY} = \sqrt{F}$ in hidden sector to few TeV leads to different gravitino/goldstino and DM sectors ➔ light, possibly long-lived particles

- Sgoldstino S(P)
  - Massless at tree level but massive via loop corrections
  - Coupling e.g. $L_{eff} \propto \frac{M_{YY}}{F} SF^{\mu\nu} F_{\mu\nu}$
  - Naturally light in no-scale SUGRA and GMSB
  - Direct production: $gg$ fusion,
  - Indirect production: heavy hadron decays $D \rightarrow \pi S(P) \; D_s \rightarrow K^+ S(P)$
  - Decay: $X \rightarrow \pi^+\pi^- , \pi^0\pi^0 , l^+l^- , \gamma\gamma$

- Neutralino in R-Parity Violating SUSY
  - LSP can decay into SM particles
  - Light neutralino with long lifetime $\tau_{\tilde{X}} < 0.1 s$ (BBN)
  - Production: heavy meson decays $D \rightarrow \nu \tilde{X} , \; D^\pm \rightarrow l^\pm \tilde{X}$
  - Decay: $\tilde{\chi} \rightarrow l^+l^-\nu$

- Hidden Photinos, axinos and saxions....
Use slow beam extraction as for NA, but 1 sec flat top

- SHiP cycle length is 7.2 s (note: CNGS cycle was 6 s)
- $4 \times 10^{13}$ ppp is historical maximum for slow extraction
  - Unavoidable losses on septum concentrated in 1 second!
  - Expect $4 \times 10^{11}$ protons per spill to hit wires: $T \rightarrow 800 \, ^\circ C$
    (operational limit is $1000 \, ^\circ C$)
  - Radioactivity, vacuum degradation, sparking, wire damage,…

Improvements needed
- Instrumentation for optimal extraction and reproducibility
- Novel methods for beam extraction?
Current splitter 1 magnet to be replaced with “three-way” splitter
- Bipolar, larger horizontal aperture and laminated yoke

Beam sweeping according to Archimedean spiral to reduce power density on target
Optimization of geometrical acceptance for a given $E_{\text{beam}}$ and $\Phi_{\text{beam}}$

- Hidden particle **lifetime** (~flat for longlived)
- Hidden particle **production angles** (~distance and transversal size)
- Hidden particle **decay opening angle** (~length and transversal size)
- Muon flux (~distance and acceptable occupancy)
- Background (~detector time and spatial resolution)
- Evacuation in decay volume / technically feasible size ~ W:5m x H:10m

Acceptance saturates ~40m – 50m
### NA62-like straw detector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of a straw</td>
<td>5 m</td>
</tr>
<tr>
<td>Outer straw diameter</td>
<td>9.83 mm</td>
</tr>
<tr>
<td>Straw wall (PET, Cu, Au)</td>
<td></td>
</tr>
<tr>
<td>PET foil thickness</td>
<td>36 μm</td>
</tr>
<tr>
<td>Cu coating thickness</td>
<td>50 nm</td>
</tr>
<tr>
<td>Au coating thickness</td>
<td>20 nm</td>
</tr>
<tr>
<td>Wire (Au-plated Tungsten) diameter</td>
<td>30 μm</td>
</tr>
<tr>
<td>Number of straws in one layer</td>
<td>568</td>
</tr>
<tr>
<td>Number of layers per plane</td>
<td>2</td>
</tr>
<tr>
<td>Straw pitch in one layer</td>
<td>17.6 mm</td>
</tr>
<tr>
<td>Y extent of one plane</td>
<td>~10 m</td>
</tr>
<tr>
<td>Y offset between straws of layer 1 &amp; 2</td>
<td>8.8 mm</td>
</tr>
<tr>
<td>Z shift from layer 1 to 2</td>
<td>11 mm</td>
</tr>
<tr>
<td>Number of planes per view</td>
<td>4</td>
</tr>
<tr>
<td>Y offset between plane 1 &amp; 2</td>
<td>4.4 mm</td>
</tr>
<tr>
<td>Z shift from plane 1 to 2</td>
<td>26 mm</td>
</tr>
<tr>
<td>Z shift from view to view</td>
<td>100 mm</td>
</tr>
<tr>
<td>Number of views per station</td>
<td>4 (Y-U-V-Y)</td>
</tr>
<tr>
<td>Stereo angle of layers in a view Y,U,V</td>
<td>0, 5, -5 degrees</td>
</tr>
<tr>
<td>Z envelope of one station</td>
<td>~34 cm</td>
</tr>
<tr>
<td>Number of straws in one station</td>
<td>9088</td>
</tr>
<tr>
<td>Number of stations</td>
<td>4</td>
</tr>
<tr>
<td>Z shift from station 1 to 2 (3 to 4)</td>
<td>2 m</td>
</tr>
<tr>
<td>Z shift from station 2 to 3</td>
<td>5 m</td>
</tr>
<tr>
<td>Number of straws in total</td>
<td>36352</td>
</tr>
</tbody>
</table>

### HS tracking system

- **Straws in test beam 2016**
  - Study sagging effects and compensation
  - Read out of signal, attenuation / two-sided readout
- **Upstream straw veto may be based on same technology**

**Horizontal orientation of 5m straws**

**First production of 5m straws at JINR**

**JINR Dubna (NA62, SHiP): Straws**

**St Petersburg (CMS, SHiP): Infra**
Tracker performance

- Critical tasks: Decay vertex, DOCA, $\chi^2$, impact parameter at target of decay hypothesis, ...

- Assuming NA62 parameters
  - Material budget per station 0.5% $X_0$
  - Position resolution 120 $\mu$m per straw, 8 hits per station on average

\[ \left( \frac{\Delta p}{p} \right)^2 \sim [0.49\%]^2 + [0.022\%/(GeV/c)]^2 \times p^2 \]

\[ \text{Momentum resolution is dominated by multiple scattering below 20 GeV/c} \]
(For HNL $\rightarrow \mu\pi$, 75% of both decay products have $p<20$ GeV/c

- Vertex resolution (also driven by multiple scattering and $\frac{\Delta p}{p}$):
  \[ \sigma_{xy} \sim \mathcal{O}(mm), \ \sigma_z \sim \mathcal{O}(cm) \]
Critical task: Coincidence of decay products

Two options: scintillating bars (NA61/SHINE, COMPASS) and MRPC (ALICE)

Main challenges (< 100 ps resolution) requiring R&D
- Long scintillating bars with large attenuation length
- Read out by SiPM arrays
- Embed SiPM arrays throughout scintillator along bar length to improve timing and position resolution
- Time alignment

120 cm long strips, 3 cm wide pitch
Actual intrinsic time resolution ~20ps
**PID: ECAL/HCAL**

- **Critical tasks**
  - Identify $e$, $\gamma$, $\pi^0$
  - Discriminate $e/\pi$
  - Improve $\mu/\pi$ discrimination

- **Shashlik type designs**

- **ECAL design**
  - Dimensions: $6\times6$ cm$^2$
  - Radiation thickness: $22.5$ $X_0$
  - Energy resolution: $5.7%/\sqrt{E} \oplus 0.3\%$
  - Overall dimension (TP): W:5m x H:10m x D:50cm
  - $\Rightarrow$ 2876 modules and 11504 cells (readout channels)

- **HCAL design**
  - Dimensions: $24\times24$ cm$^2$
  - Interaction thickness: $1.7\lambda / 4.5\lambda$
  - Overall dimension (TP): W:5m x H:10m
  - $\Rightarrow$ 1512 modules/cells (readout channels)

- **Main challenge is ECAL calibration**
  - $2 \times 10^9 \mu$ /day (MIP) and $1.3 \times 10^6$ e /day (from $\mu \rightarrow e$)
  - $\Rightarrow$ Equalization on MIP, energy scale with $E/p$ for electrons per cell
  - $\varnothing(100)$ electrons/cell/day $\Rightarrow$ ~1% calibration accuracy in a week

---

**Protvino (COMPASS, SHiP): ECAL, HCAL**

**ITEP (LHCb, SHiP): ECAL, HCAL**

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KEK seminar, Japan, April 19, 2016
Critical tasks: $\mu$ and $\pi$ identification with high efficiency

Challenge

- Tough as pions decay in flight before PID system
  - 20% of the pions at 2GeV, 10% at 5GeV, 4% at 30GeV

4 stations based on x-y plans of scintillating bars with WLS fibres and SiPM readout

MUON design

- Bar dimensions: $5 \times 300 \times 2 \text{ cm}^3$
- Number of bars: 3840
- WLS length: 23 km
- Overall dimension (TP): W:6m x H:12m
- Iron filter weight: ~1000 tonnes

$N_{2,3}(0.8 \text{ GeV}) \rightarrow \mu^\pm \pi^\pm$
PID performance

Electron efficiency >98%
Pion contamination: <2%
Neutral pion mass resolution: 5 MeV

Muon misid with ECAL+HCAL

Rejection factor for $e_\mu = 95\%$

<table>
<thead>
<tr>
<th>Energy, GeV</th>
<th>E+H1+H2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>23</td>
</tr>
<tr>
<td>1.5</td>
<td>32</td>
</tr>
<tr>
<td>2.0</td>
<td>50</td>
</tr>
<tr>
<td>2.7</td>
<td>120</td>
</tr>
<tr>
<td>3.0</td>
<td>160</td>
</tr>
<tr>
<td>5.0</td>
<td>210</td>
</tr>
<tr>
<td>10.0</td>
<td>250</td>
</tr>
</tbody>
</table>

ECAL (July), HCAL (September), MUON (October) in test beam 2015 on PS and SPS
HS signal yields

- **Ex. Expected event yield** $N_{2,3} \rightarrow \mu \pi$
  - Same procedure applied to all physics channels

- **Expected number of signal events**

  $$N_{\text{signal}} = n_{pot} \times \chi(pp \rightarrow N) \times P_{vtx}(U^2) \times A_{tot}(N \rightarrow \text{visible})$$

  - $n_{pot} = 2 \times 10^{20}$
  - $\chi(pp \rightarrow N) = 2 \times \left[ \chi(pp \rightarrow c \bar{c}) \times \mathcal{B}R(c \rightarrow N) + \chi(pp \rightarrow b \bar{b}) \times \mathcal{B}R(b \rightarrow N) \right] \times U^2$
    - $\chi(pp \rightarrow c \bar{c}) \sim 1.7 \times 10^{-3}$, $\chi(pp \rightarrow b \bar{b}) \sim 1.6 \times 10^{-7}$
    - Integral mixing angle $U^2 = U_e^2 + U_\mu^2 + U_\tau^2$ in different scenarios of flavour coupling hierarchies
  - $P_{vtx}(m, U^2)$: probability that HNL decays in SHiP fiducial volume
  - $A_{tot}(N \rightarrow \text{visible})$: detector acceptance (including reconstruction) for all final states
    - $A_{tot}(N \rightarrow \text{visible}) = \Sigma_{i=\text{visible channel}} \mathcal{B}R(N \rightarrow i) \times A(i)$

$\Rightarrow P_{vtx}(U^2) \times A_{tot}(N \rightarrow \text{visible})$ based on simulation

$\Rightarrow$ Detection efficiency entirely dominated by the geometrical acceptance

$\Rightarrow$ Typical $P_{vtx} \times A_{tot} \times \varepsilon_{\text{selection}} \sim 10^{-6}$
History and Current Status

  - EOI stimulated a lot of interest

- January 2014: EOI discussed at SPSC
  - Encouraged to produce “an extended proposal with further developed physics goals, a more detailed technical design and a stronger collaboration.”

- January 2014: Meeting with CERN Research Director S. Bertolucci
  - Proposed a task force to evaluate feasibility and required resources at CERN within ~3months
  - Supportive to the formation of a proto-Collaboration and agreed to CERN signing

- 4 SHiP Workshops/Collaboration meetings 2014-2015
  - Explore and extend physics case
  - Preparation of Technical Proposal
  - Formalize Collaboration with >200 experimentalists and theorist from 45 institutes in 14 countries
  - Russian participation:

- Technical Proposal and Physics Proposal submitted to April SPSC